BLAST MITIGATION IN CONFINED SPACES BY ENERGY ABSORBING MATERIALS

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Abstract

Tests have been performed with different explosives (balanced as well as underbalanced with respect to Oxygen) at different loading densities (0.1 - 4 kg/m^3) with different additives (e.g. water, glycol and foam) to get a basis for a better understanding of the possible mitigation effects on stored ammunition.

Water has a mitigational effect on the blast wave from an explosion. This surpression of the pressure works for both balanced and underbalaced agents and seems to be independant of the loading density. The quantitative effect is depending on the way the water is distributed but the tests show that the effective charge size can be reduced with more than 50 %.

Acknowledgement

This work is the result of a cooperation between FortF[1], Confortia[2] and FOA[3] under FOA contract No 93260802. The tests were performed by FOA at their Test Stations in Märsta[4] and in Grindsjön under supervision of Anders Carlberg and Rickard Forsén, respectively. The tests with foam were emasculated thanks to Andrew Medin, FOA.

Introduction

The idea to use water to mitigate the effects of a detonation has been illustrated before, e.g. by one of the authors 1974 /1/. Since then, the long-term problem of having water in a dehumified environment has been solved and today there exist many solutions for practical use of water as an energy absorber /2/. However, the idea of having water in explosives chambers is disputed since there is no good explanation to the phenomena which also takes into account the possible explosive steam expansion. Furthermore, there is a lack of rules how to quantify the effect.

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[1] FortF, Royal Swedish Fortifications Administration, abolished June 30^{th,} 1994.
[2] Confortia, federal company continuing FortF:s activities within design and R&D
[3] FOA, National Defence Research Establishment
[4] Formerly FortF:s Test Station

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Typically, the Heat of Detonation for an explosive is in the range 5 to 10 MJ/kg which can be compared to 2.5 MJ/kg, the energy needed to vaporize water. If, however, a complete deflagration of the explosive is considered, more energy is available if there is an afterburning. This is the case for any underbalanced explosive and almost every military HE has an Oxygen deficiency. For TNT, which is extremely underbalanced, the Heat of Combustion is 2.5 times the HoD. The difference is, of course, smaller if the HE is more balanced, see Table 1.

If a charge is ignited the HoD determines the strength of the incident blast wave. The slower afterburning takes place where Oxygen is available, that is on the surface of the expanding hot reaction products containing carbon and carbonmonoxide. In an unconfined situation the afterburning can be seen as a fire-ball with the radius growing to appr. 1 $m/kg^{1/3}$. (The size is of course depending on the kind of explosives used.) In a confined situation such as a detonation in a room the reflexions from the walls will contribute to a more efficient mixing between the hot reaction products and the Oxygen content in the room but in this case the after-burning is limited by the Oxygen available in the room. While the peak pressure is depending on the detonation energy and the distance, the chamber pressure, p_{ch}, (sometimes called the quasi-static pressure or low frequency pressure) is depending on the combustion energy. This is, however, not necessarily proportional to Q since it is depending on if enough Oxygen is available or not. Thus the relation
p_{mean} = f( ) is not linear, see Fig 1. The upper limit for a possible complete afterburning process can easily be estimated from the chemical formula and is given for some agents in Table 1.

Now, if a water supply just stops the afterburning there should be no effect on the chamber pressure if either the explosive is Oxygen balanced or the loading density is above the limit given in Table 1. Most tests performed in this area have been made at very low loading densities and with underbalanced explosives. As a contrast, in many ammunition storages is much larger than $_{limit}$.

The physical effects of liquid water in the proximity of a charge detonating in air have not been described. On the one hand it takes energy to heat and to vaporize water but on the other hand the vaporization gives an increase of the volume. The mole volume for a gas at normal pressure and temperature is 2,24 10^{-2} m^3 and 1 mole H_2O is 18 g, thus 1 kg water (1 l) gives 56 moles of gas or 1.24 m^3. (The gas volume of 1 kg water is thus of the same order of magnitude as the gas volume from 1 kg HE, Cf. Table 1.) This possible steam expansion when heat is transferred to water has to be considered in the risk analysis of many industrial environments such as in the pulp industry and in nuclear plants. The question is if an explosive boiling of water might occure at an explosion in an ammunition storage with water supply.

Table 1 Some HE-data. Comp B is a mixture of RDX and TNT.

Name	Formula	HoD MJ/kg	HoC MJ/kg	ρ_{limit}[a] kg/m^3	gas volume[b] m^3/kg HE	Oxygen balance %
TNT	$C_7H_5N_3O_6$	5.4	14.5	0.4	1.1	-74
RDX	$C_3H_6N_6O_6$	6.2	8.9	1.4	0.8	-22
PETN	$C_5H_8N_4O_{12}$	6.2	7.6	3.0	0.9	-10
Dynamex	$C_{0.76}H_{4.07}N_{2.04}O_{3.63}$	4.7	4.7	-	0.9	+1

[a] maximum loading density for complete combustion
[b] at complete combustion

Table 1 Some HE-data. Comp B is a mixture of RDX and TNT.

Fig 1.

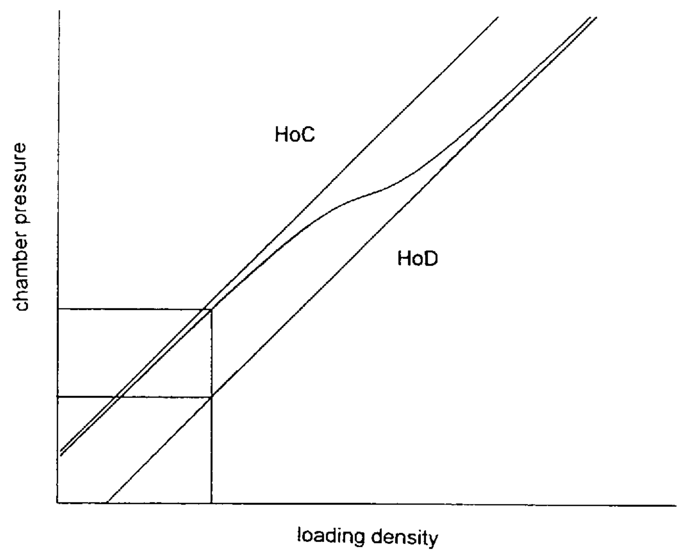


Fig 1. Chamber pressure as function of the loading density. If the explosive is Oxygen deficient the relations are depending on the size of the room. If a complete combustion is possible p ~ HoC (left part) while p ~ HoD at large loading densities. If water has effect only on the afterburning it makes a difference only when HoD ≠ HoC.

Complications for the numerical handling of the problem are the acceleration and atomizing of the water and the passage of blast waves through layers, drops and bubbels. It is known that changes of the impedance in complex media have influence on the transmitted energy. A similiar situation in this sence is achieved if the water before the ignition is distributed in the volume as a foam. When long-term storage of ammunition is considered foam is, however, of little interest.

Water is better than air to decelerate the debris from an explosion but sand is, of course, superior, see Table 2, as a mean to stop transitions of detonations due to fragment impacts. Tests show that foam is efficient to catch particles of dust from an explosion, /3/, whereas it has little effect on debris.

Table 2 **Relative penetration depth in different materials, /4/**

Material:	Steel	Concrete	Sand	Water	Snow (wet)	Snow (dry)
Depth:	1	6	18	50	70	140

Table 2 Relative penetration depth in different materials, /4/

Tests

In the test reported here three types of explosives have been used:

TNT, Oxygen deficient
Dynamex, commercial explosive, /6/, Oxygen balanced
Mil. Plastic Explosives, based on PETN, Oxygen deficient

Tests were performed

with and without water.

The charges were placed

inside
close to
at some distance off the additives

and ignited in

a completely closed room
an open end tube.

In some cases the water was replaced by

glycol
turpentine
sand.

It was considered in the planning of the tests, that the flammable additives might add extra energy to the event but probably not to the front pressure close to the charge. These tests were performed to have a variation of the Heat of Vaporization, see Table 3, and the density. (Glycol is used added to water to prevent freezing.)

Since FOA at the same time, in another project, was studying the influence of foam on an unconfined detonation it was possible to perform a comparative test with foam in a closed room.

Table 3

	density kg/m^3	HoV MJ/kg	Boiling point °C	Specific Heat MJ/kg K
water	1000	2.26	100	0.0042
turpentine, ($C_{10}H_{16}$)	840	0.29	180	0.0018
glycol, $(CH_2OH)_2$	1160	0.80	197	0.0024

Table 3

Test Set Up and results

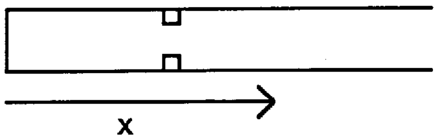
The tests were performed in Shock Tube III and IV in Märsta and in a closed-room-facility in Grindsjön. Only a brief description of these devices is given in this context.

Shock Tube III

Shock Tube III was in the tests arranged as shown in Fig 2. The charges were detonated on the center-line of the steel tube chamber and the side-on pressure was recorded in the lined-in concrete tube. The total amount of explosives was 100 kg divided into two 50 kg charges separated 1.5 m, see Fig 3. To establish a comparison between the two explosives additional tests with TNT but without water must be performed.

Fig 2. Description of Shock Tube III and IV as arranged for the tests.

chamber, constriction, tube, open end



Tube IV: x (m)	Σ (m)	A (m²)
1	1	1.90
0.63	1.63	0.302 (circular)
4.55	6.18	1.90 (MP1)
3.05	9.23	1.90 (MP 2)
1.00	10.23	1.90 (MP 3)
10.80	20.03	1.90 (MP 4)
0.50	20.53	1.90 (40 bend)
7.03	27.56	1.90 (open end)

Tube III: x (m)	Σ (m)	A (m²)
7	7	3.14 (circular)
0.57	7.57	0.44 (circular)
4.80	12.37	4.00
2.65	15.02	3.14 (circular)
1.8	16.82	3.80 (circular)
7.5	24.32	4.00
3.85	28.17	4.43
6.25	34.42	4.00
41.11	75.53	4.40 (MP 13)
25.00	100.53	4.40 (MP 14)
25.00	125.53	4.40 (MP 15)
25.00	150.53	4.40 (MP 16)
50.00	200.53	4.40 (MP 18)
27.97	228.50	4.40
5.75	234.25	5.28
5.75	240.00	5.72 (open end)

Fig 2. Description of Shock Tube III and IV as arranged for the tests.

Fig 3. Dynamex charges and adjoining 25 l water tanks in Shock Tube III. To the left W/Q = 1 and to the right a view through the 0.75 m diameter connection to the tunnel when W/Q = 5.

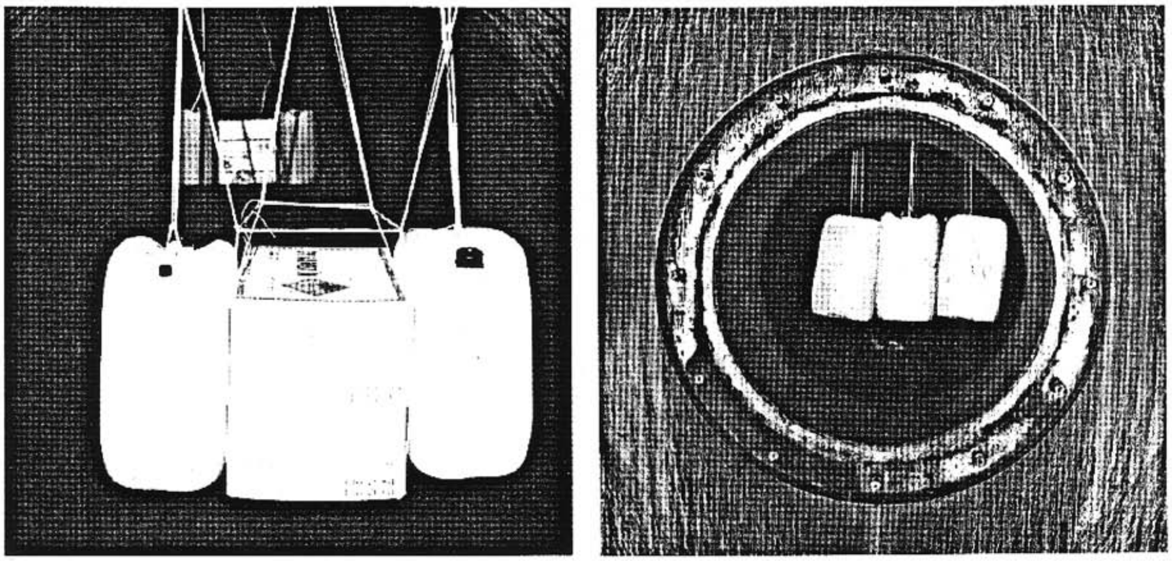


Fig 3. Dynamex charges and adjoining 25 l water tanks in Shock Tube III. To the left W/Q = 1 and to the right a view through the 0.75 m diameter connection to the tunnel when W/Q = 5.

At evaluation of the pressure-time history some decisions have to be made. Here p_{front} is the result of a fit to an exponential decay, p_{mean} is the mean value under the same time while p_{max} simply is the maximum recorded pressure. The length of the time interval used for the fit and the mean will of course have effect on the magnitudes of the evaluated pressures, see Fig 5. In these tests it is chosen to 3 ms and then there is no significant difference between p_{front} and p_{mean} since we have a long duration wave. Any of these two is a better measurement of the pressure than to give the even more arbitrary peak value.

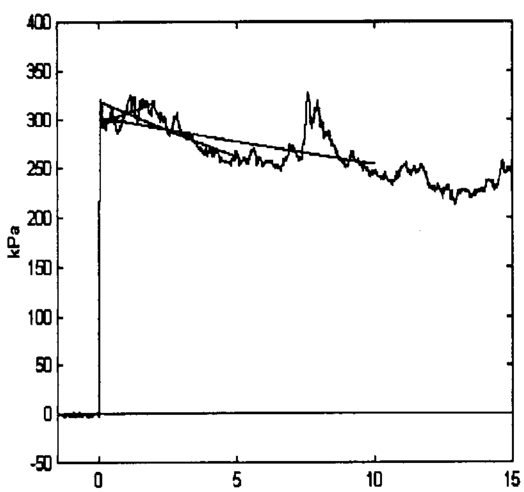
t_+ is here defined as the time to the maximum impulse density, i_+. This definition seems to be more adequate here than the classic one since it ignores temporary pressure drops.

The magnitude of the evaluated value of i_+ is very sensitive to errors in the measuring technique since the duration is long. The signals were digitally recorded and though the time interval was as long as 1s this appears to be too short to get the impulse density to approach a constant value, i.e. to get the pressure back to the ambient value. The later part of the pressure-time history is affected by the rarefaction wave from the open end of the tube causing a pressure drop and thus i_+ may be lower than for a long tunnel. But the heat load from the hot reaction products may cause a similar result since the gauges had a negative temperature sensitivity. Now, with a short recording time we can never be sure that the gauges had a proper heat protection and are giving the juste pressure level. Thus, the magnitude of i_+

may be uncertain. Only when the heat takes the signals down below the level corresponding to vacuum we know for certain that the signal is false. In order still to have some mesaurements of the impulse, i_{100} is evaluated as the impulse density of the first 100 ms. This time is chosen since the heating effect during that time probably is negligible. (The deceleration of the contact surface enclosing the reaction product is greater than that of the blast front and in open space and it stops at appr. 1 m/(kg HE)$^{1/3}$. Transferring the corresponding volume to the tube gives that the range of the reaction products is appr. 100 m for a 100 kg charge, i.e. to MP 14, see Fig 2.)

Some results are shown in Figs below. (More details about the tests are published in /8/.) In Fig 5 the pressure decrease at MP 18 appr. 200 ms after the front (t = 450 ms) is caused by the rarefaction wave from the open end. This wave is travelling upstream with the sonic velocity and the influence at MP 16 (50 m further upstream) is thus delayed with appr. 150 ms (t = 600 ms). Only at MP 18 the time frame was long enough to show the impulse curve flattening out and only then we had an i_+ as identified above. In Fig 6 the effects of water are illustrated and the results are summarized in Figs 7 - 8.

Fig 4 The evaluated front pressure is depending on the time frame. Here "front" referes to an exponential fit (drawn over the time considered) and "mean" to the mean value over the same time. (From MP 13, 100 kg TNT, W/Q = 1.)



time ms	front kPa	mean kPa
1	300	298
2	295	296
5	319	289
10	302	278

Fig 4 The evaluated front pressure is depending on the time frame. Here "front" referes to an exponential fit (drawn over the time considered) and "mean" to the mean value over the same time. (From MP 13, 100 kg TNT, W/Q = 1.)

Fig 5.
Registrations from a test in Shock Tube III given in a common time frame.

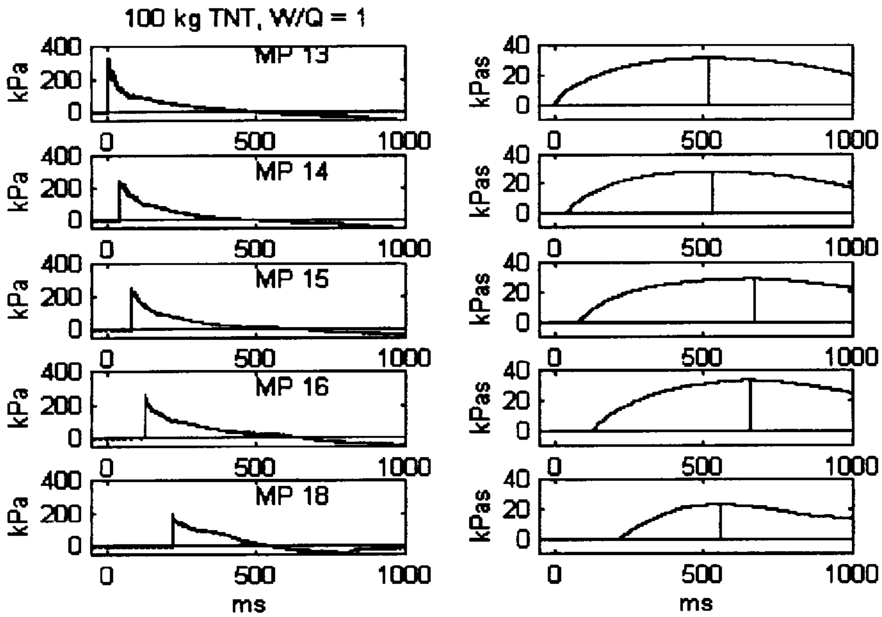


Fig 5. Registrations from a test in Shock Tube III given in a common time frame.

Fig 6. Samples of registrations from MP 18 for different water to charge ratios (W/Q). Q = 100 kg Dynamex.

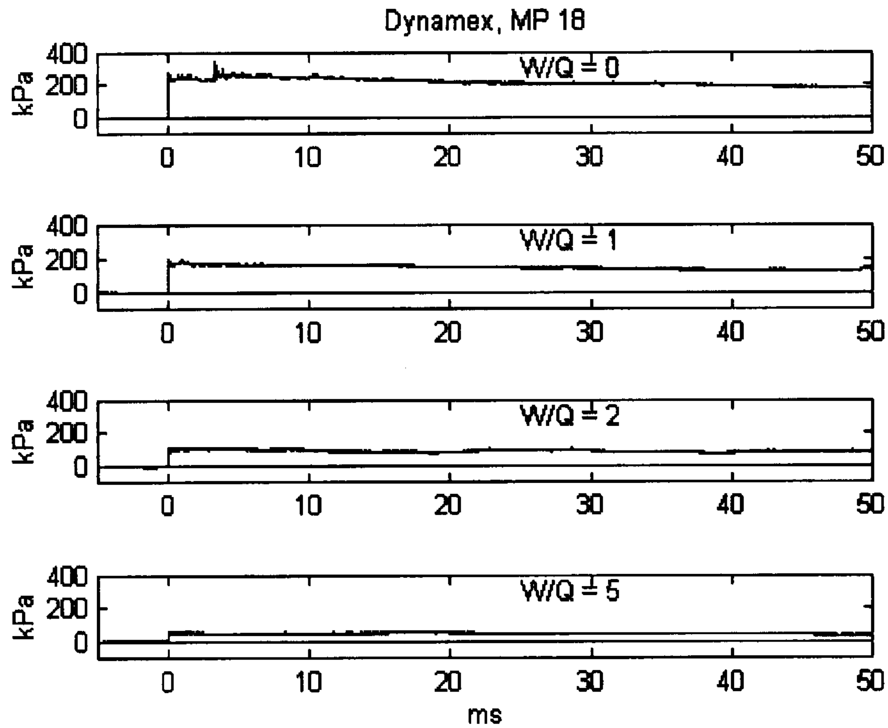


Fig 6. Samples of registrations from MP 18 for different water to charge ratios (W/Q). Q = 100 kg Dynamex.

Fig 7 p_{front} and i_{100} at different locations in Shock Tube III. 100 kg Dynamex

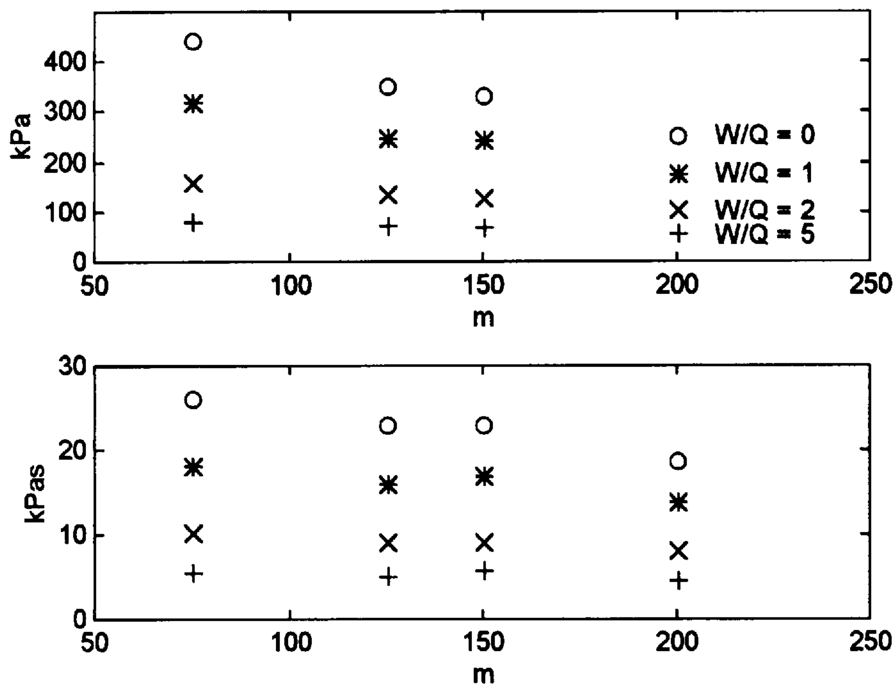


Fig 7 p_{front} and i_{100} at different locations in Shock Tube III. 100 kg Dynamex

Fig 8 p_{front} and i_{100} at different locations in Shock Tube III. 100 kg TNT.

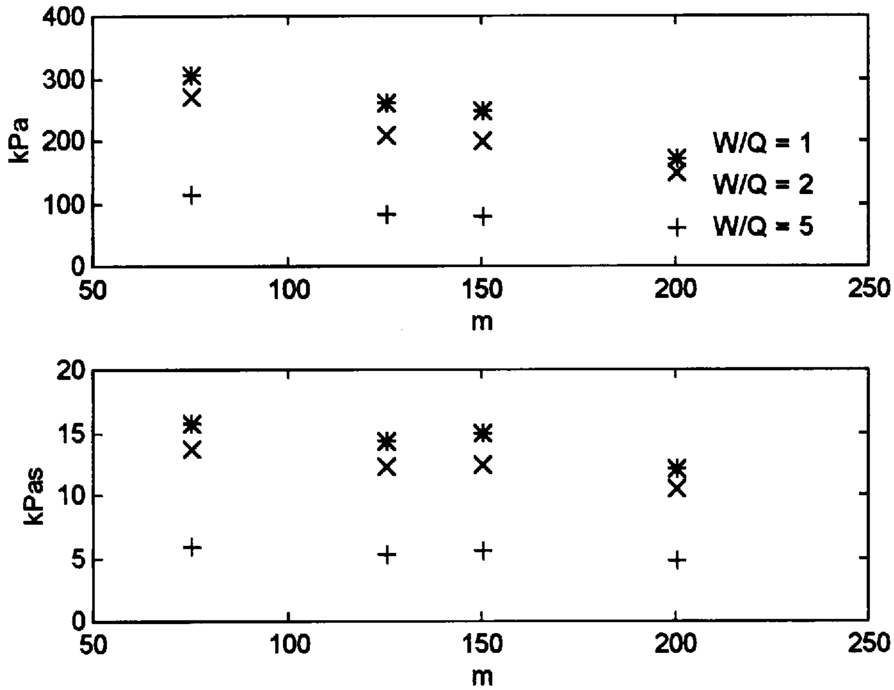


Fig 8 p_{front} and i_{100} at different locations in Shock Tube III. 100 kg TNT.

Shock Tube IV

Only the part of Shock Tube III described in Fig 2 was used, see Fig 9. Some results are shown in Figs below and are summarized in Figs 13 -14. Here p_{front} is the result of a 10 ms fit to an exponential decay. More details are given in /8/. In Fig 10 "in" stands for the charge detonating inside a water bag otherwise four water bags were used (around the charge) and "close" means that they were in contact with the charge and "far" that they were at the distance 0.3 m off the charge.

From Fig 11 can be seen that the rarefaction wave from the open end has a significant effect on the overpressure only at MP 4. Compared to the tests in the bigger tube the heat load is now less disturbing, thus i_{max} can be evaluated.

Fig 9. A test set up with four waterfilled bags close to a 1 kg charge in Shock Tube IV. Photo taken from the end of the tube closed during the tests.

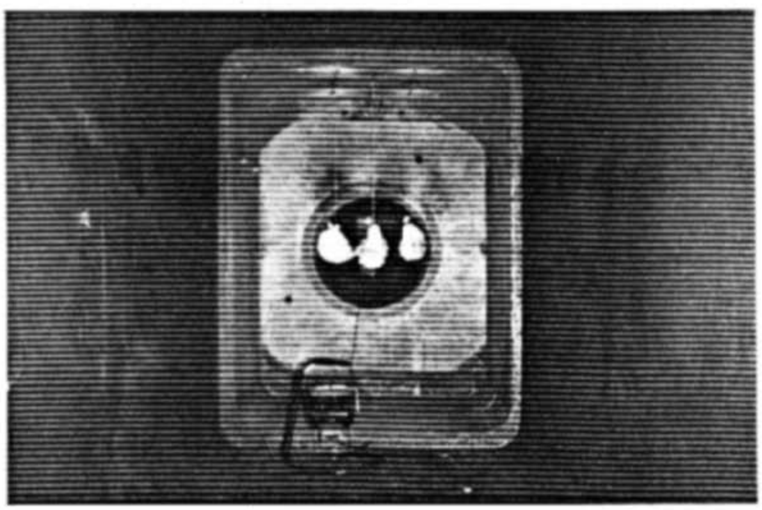


Fig 9. A test set up with four waterfilled bags close to a 1 kg charge in Shock Tube IV. Photo taken from the end of the tube closed during the tests.

Fig 10 Samples of registrations from MP 1. Q = 1 kg, TNT (left) and Dynamex (rigth). In the three lower registrations water was added (W/Q = 5).

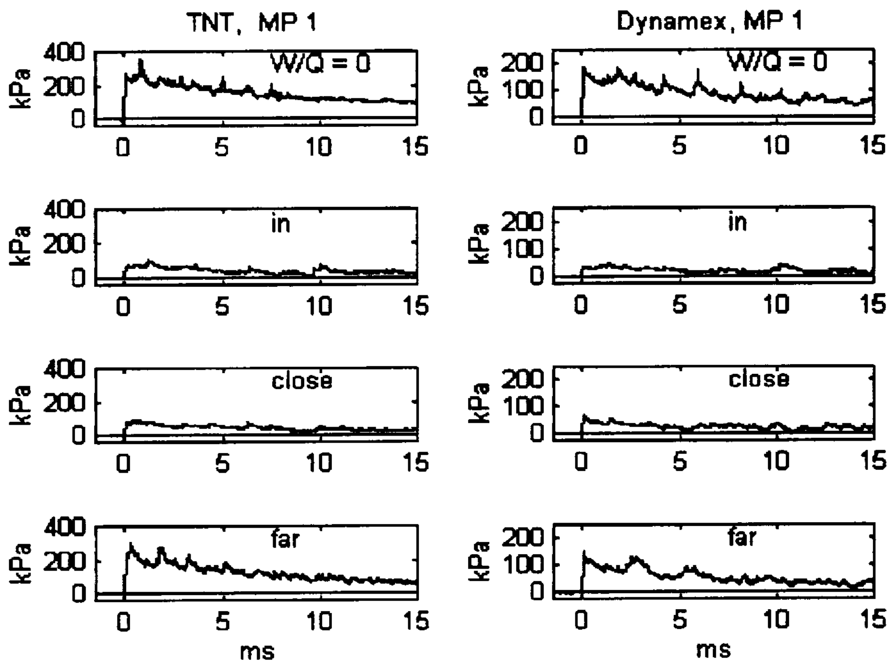


Fig 10 Samples of registrations from MP 1. Q = 1 kg, TNT (left) and Dynamex (rigth). In the three lower registrations water was added (W/Q = 5).

Fig 11.
Registrations from a test in Shock Tube IV given in a common time frame.

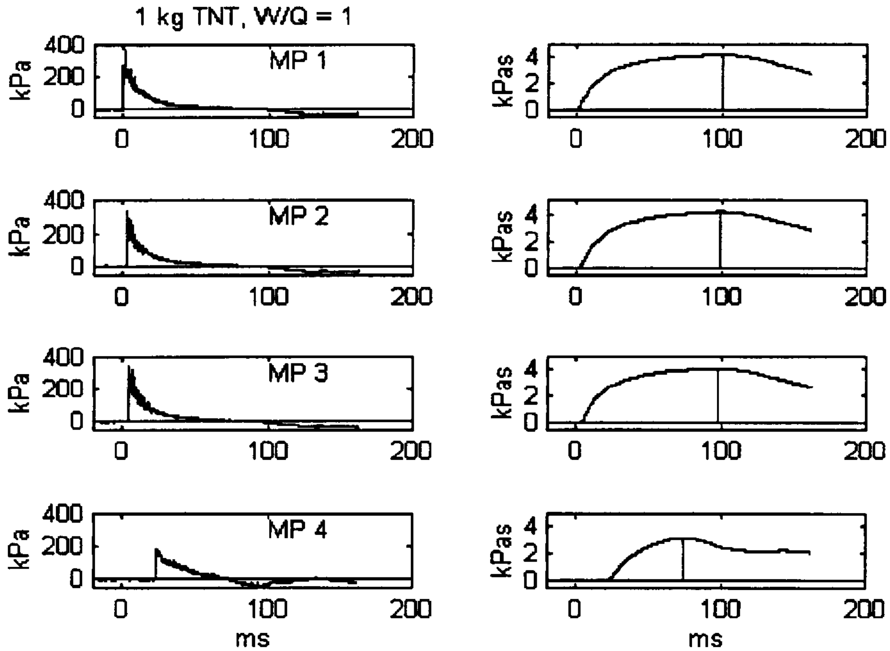


Fig 11. Registrations from a test in Shock Tube IV given in a common time frame.

Fig 12 Effects of different additives, 1 kg TNT, MP 2. In all cases the additives had the same volume, 5 l.

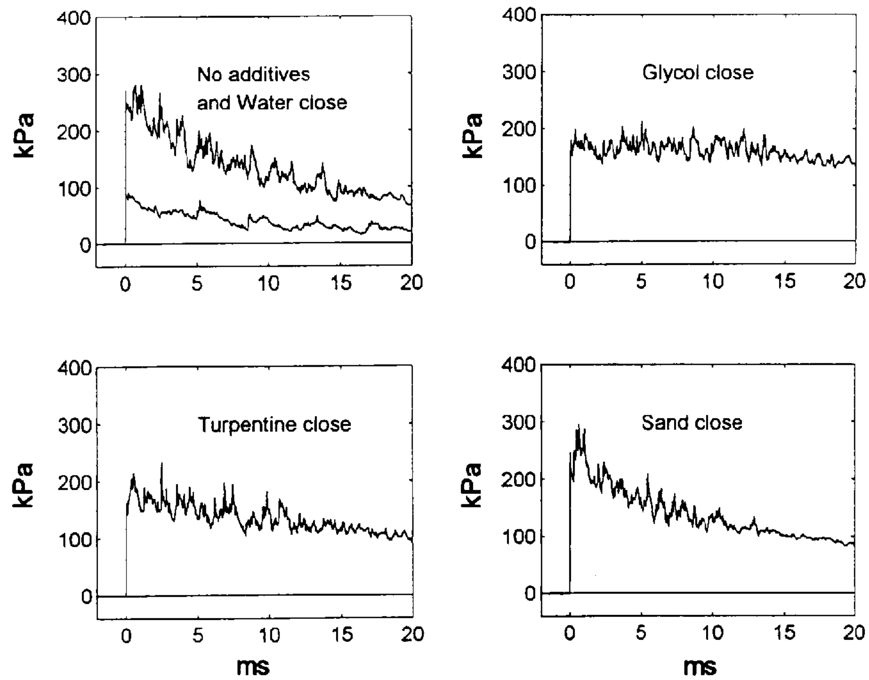


Fig 12 Effects of different additives, 1 kg TNT, MP 2. In all cases the additives had the same volume, 5 l.

Fig 13 p_{front} and i_{max}at different locations in Shock Tube IV. 1 kg TNT. W/Q = 0 or 5.

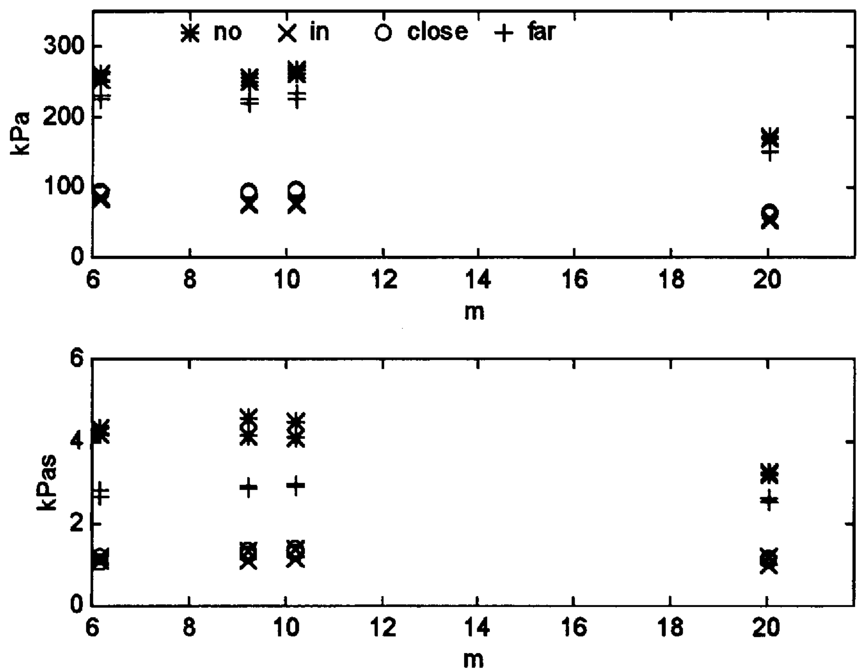


Fig 13 p_{front} and i_{max}at different locations in Shock Tube IV. 1 kg TNT. W/Q = 0 or 5.

Fig 14 p_{front} and i_{max} at different locations in Shock Tube IV. 1 kg Dynamex. W/Q = 0 or 5.

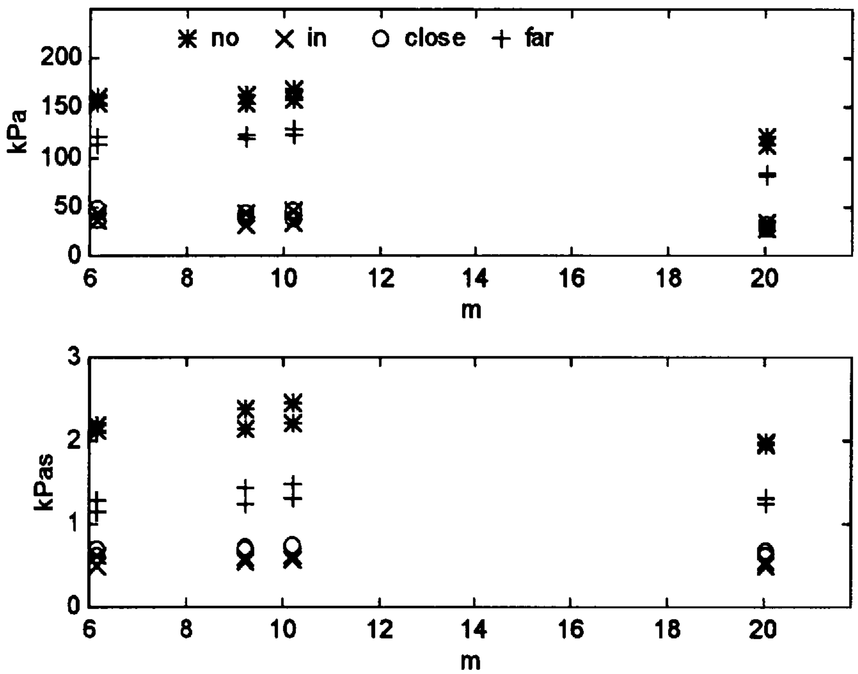


Fig 14 p_{front} and i_{max} at different locations in Shock Tube IV. 1 kg Dynamex. W/Q = 0 or 5.

Fig 15 p_{front} and i_{max} at different locations in Shock Tube IV. 1 kg TNT. Comparison between different additives.

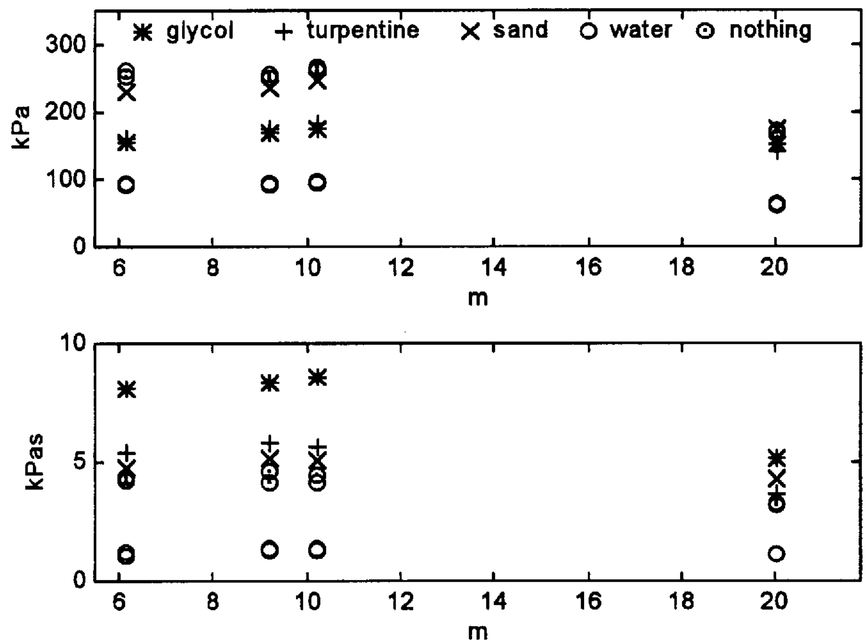


Fig 15 p_{front} and i_{max} at different locations in Shock Tube IV. 1 kg TNT. Comparison between different additives.

Closed Chamber

Concise summary:

HE:	Plastic explosive based on PETN $Q = 0.5$ kg, $\rho = 0.13$ kg/m^3	
W/Q:	0, 5	variation of the water distribution
	water, foam	

This device is used for testing construction elements such as walls under long duration loads. In our tests a completely closed 3.75 m^3 chamber was formed by attaching the test specimen to the 5-walled concrete cubicle and the charge was detonated in the center of the room, see Fig 16.

Fig 16 The closed-room facility in Grindsjön as arranged for the tests

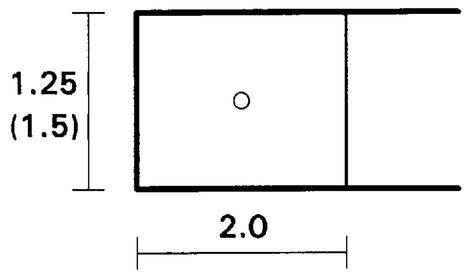


Fig 16 The closed-room facility in Grindsjön as arranged for the tests

The test specimen, a scaled reinforced concrete wall, was known from previous tests to stand the load from 0.2 kg but not from the load of 0.5 kg. More precisely, the wall was calculated, /7/, to stand a load limited by the hyperbola $p_c/p + i_c/i = 1$ with the asymptotes $p_c = 26$ kPa (long duration) and $i_c = 1.5$ kPas (short duration). The registrations are omitted here. The results in short can be found in Table 4, and some evaluated values are given in Fig 16 together with the mentioned hyperbola and some previous /7/ test results.

Table 4 Summary of tests in closed room

Charge size (kg)	Comments	
0.2	/7/	unbroken
0.5	/7/	broken
0.5	W/Q = 5, four bags in contact with the charge	unbroken, deformed
0.5	foam filled room	intact
0.5	W/Q = 5, four bags 0.3 m from the charge	broken

Table 4 Summary of tests in closed room

Fig 17 Results from the closed chamber.

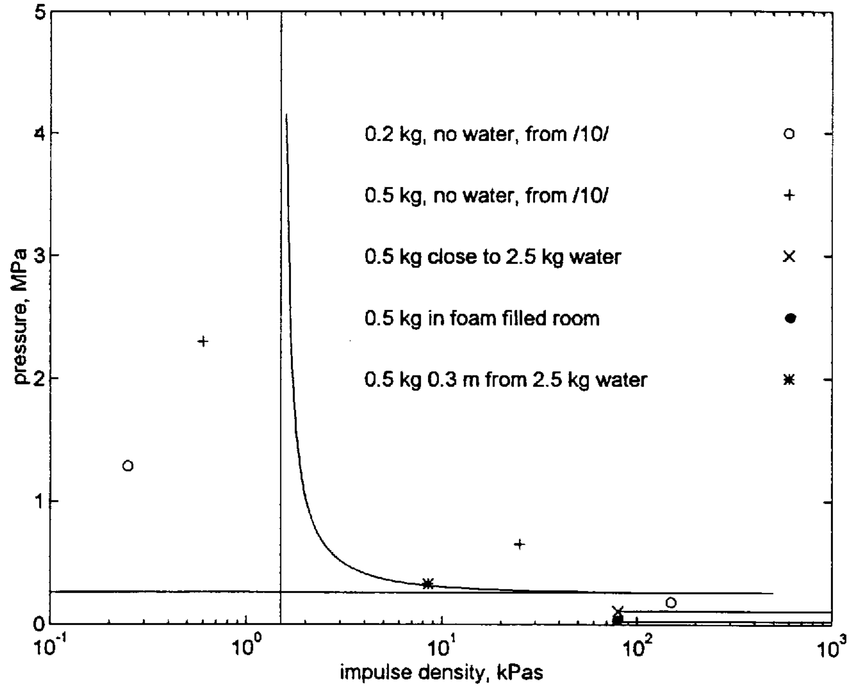


Fig 17 Results from the closed chamber.

The hyperbola $p_c/p + i_c/i = 1$ with the asymptotes $p_c = 26$ kPa and $i_c = 1.5$ kPas are giving the approximate limiting load for the wall. Thus the wall could stand the high front pressure (given to the left for the no water case only) since the associated impulse was low but not the long time mean value pressure (to the right) if the pressure and impulse are above the curve. In case the wall ruptured the impulse is not fully developed while in case it lasted the recording time was in two tests (indicated with a horisontal line) too short to give the maximum impulse.

Discussion

The mitigation effects of water were verified and they seem to be independant of the loading density in the tested range. Furthermore, it seems to be no major difference between the effect on an Oxygen deficient explosive (TNT) and a balanced explosive (Dynamex), see e.g. Fig 10. Thus water has effect on the generated blast. It is obvious that the reductional effects of the water bags are depending on the distance to the charge. Some minor differences in Fig 10 can be explained by variations in the charge geometry.

It was out of the scope of this project to make an energy comparison. Since the two explosives were detonated in different shapes such a comparison could anyway be misleading.

It is interesting to see the filtering effect of water on the pressure-time history. Similar effects, "noise" reductions, have been achieved with foam in blast simulators /5/.

At the test in Tube III we noticed that there was no water left when W/Q = 1 and that the wall was just wet when W/Q = 2. After the tests with W/Q = 5 it was appr. 0.1 m^3 water remaining on the cylindrical floor. Similar results were obtained in the other test set-ups. These results indicate that there might be a saturation point.

The tests in the closed chamber were very succesful. In these tests it is of course irrelevant if the pressure is due to the detonation or to an explosive boiling - the transducer is giving the resulting pressure. Besides, the test wall acted as a passive transducer.

In the foam test the room was filled with a medium density foam of the kind used by the fire-brigades through ϕ mm temporary hole and the filling process consumed 60 kg water and 2 kg foam additives compared to 2.5 kg water in the previous tests. The fact that foam was more efficient than concentrated water is not surprising.

A comparison between the tests with water and glycol, etc, indicates that a difference in the heat capacities affects the load (see upper diagram in Fig 15) but it seems as the addition of glycol will add impulse, see Fig. 12. This can be understood since we in principle have a FAE device if glycol or turpentine is added. A straight forward calculation of the possible energy release shows, however, that only a minor part of the fuel could have reacted (burned) during the first milliseconds, otherwise the impulse would have been much higher.

A better way to get a variation of the possible heat sinks might have been to use carbon tetrachloride ($C\,Cl_4$) with a HoV-value just a 10^{th} of that of water or to use ice with one additional phase transition. In the first case, however, environmental effects have to be considered. Tests with these to additives could easily be performed and when water may be used in amunition storages in Sweden the situation with ice must anyway be considered. Replacing water with glycol to avoid freezing seems to be to increase the hazard.

The relations to estimate the blast wave in a tunnel given in /4/ may be used to get a quantitative measure of the reductional effect. Such an estimate can of course only be approximative since the used formulas apply only to straight tunnels with no constrictions and end effects and since the water supply may have different effects on p and i. Fig. 18 gives the results where a reduction of the charge weight has been calculated which corresponds to the measured reduction of the front pressure in the same tunnel geometry.

Fig 18 Estimated charge reduction caused by water addition

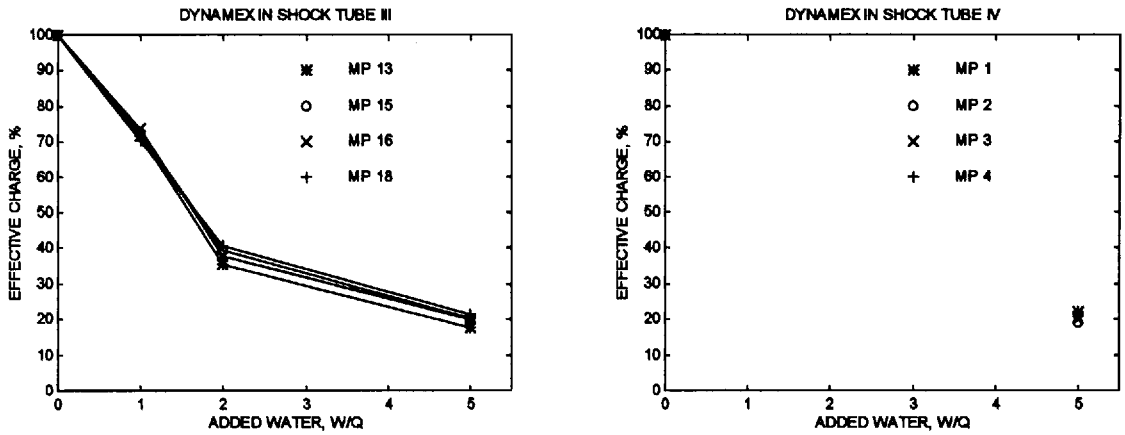


Fig 18 Estimated charge reduction caused by water addition

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